

NEW APPROACHES IN PROCESS MONITORING FOR FUEL CYCLE FACILITIES*

Benjamin B. Cipiti and Nathan Shoman
Sandia National Laboratories
P.O. Box 5800, MS 0747, Albuquerque, NM 87185-0747

ABSTRACT

Process Monitoring has been part of the safeguards approach for fuel cycle facilities for many years, but its use has been limited in the past. For example, aqueous reprocessing plants may use bulk data from level measurements to generate a bulk material balance that can be correlated with traditional accountancy measurements. However, advanced measurement technologies and modern data analytics approaches may provide new approaches for Process Monitoring. New facility types may also drive the need for better approaches. Pyroprocessing plants have unique safeguards challenges and unique measurements that could be used to monitor operations. The purpose of the work presented here is to examine improved process monitoring approaches for both aqueous and pyroprocessing facilities. Both unique measurements specific to those facility types as well as machine learning techniques to correlate various data types are being examined. The success metrics are to either improve detection probability or timeliness of detection, or reduce safeguards burden through more use of unattended monitoring systems. This work relies on safeguards performance modeling to generate simulation data for training followed by diversion or misuse scenarios for testing the approaches. The approaches being considered and preliminary results are presented.

INTRODUCTION

The key value of Process Monitoring (PM) data in a bulk handling facility is that often it can be acquired through unattended monitoring. This may include electromanometers for tank level, scales for bulk mass, online measurements like spectroscopy, or NDA measurements like neutron and gamma measurements. Current large-scale bulk handling facilities rely on sampling and destructive analysis (DA) for precision actinide measurements in order to complete an actinide balance. This requires an on-site laboratory and more burden to international safeguards. A long-term goal of international safeguards is to provide the same level of detection probability through use of unattended monitoring only. PM data may help to achieve that goal.

The difficulty with PM data is that these types of measurements usually cannot quantify actinides to low uncertainty. NDA measurements may have an uncertainty of $\pm 5-10\%$ for quantifying plutonium. If PM measurements are used to calculate a traditional actinide balance, the overall uncertainty will be too high to meet IAEA safeguards goals, and diversion detection is significantly reduced.

The purpose of this paper is to present a new approach for international safeguards that can allow use of unattended PM data to meet IAEA safeguards goals without dependence on an on-site

* SAND2018-xxxxC, Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

laboratory. This approach requires a different way of meeting the goals and could be considered in examples where traditional safeguards either will not work or will be too costly.

BACKGROUND

The International Atomic Energy Agency (IAEA) has two main goals in safeguarding a fuel cycle facility [1]:

- Timely detection of diversion of declared nuclear material
- Timely detection of undeclared production or processing of nuclear material

There are multiple ways to achieve these goals. Traditionally, precision measurements are used on inputs, outputs, and inventory change within a material balance area in order to set up a Material Unaccounted For (MUF) calculation. Various statistical tests are applied to set alarm thresholds for indicating a diversion. In general, the material balance helps protect against the above two goals, but the safeguards approach is often augmented with process monitoring, containment, and surveillance.

For reprocessing facilities under IAEA safeguards, the traditional approach has required significant sampling and laboratory analysis. This has led to the need for an on-site laboratory in the case of Rokkasho [2]. Due to the cost of on-site inspectors and laboratory analysis, there is considerable interest in moving away from the need for an on-site laboratory. Sample shipping is also becoming problematic, so reliance on other laboratories is also less desirable. In an ideal case, IAEA would like to be able to safeguard a facility with unattended monitoring only, which generally requires non-destructive analysis (NDA) that can be done automatically. The purpose of this paper is to explore how new process monitoring approaches may enable such an approach while still achieving the same IAEA goals.

This work relies on modeling and simulation to examine advanced PM approaches. The Separation and Safeguards Performance Model (SSPM) [3,4] has been used to provide training data and test the concepts under various scenarios. Multiple versions of the SSPM exist, including PUREX, UREX+, and Electrochemical models. These models use Matlab Simulink to track elemental and isotopic material flows through various unit operations. Measurement blocks are used to simulate materials accountancy and process monitoring data, and these data are fed into an inventory difference or a machine learning calculation. Diversion scenarios are used to determine the effectiveness of a safeguards design.

A PUREX SSPM version is shown in Figure 1. The gray blocks represent the processing vessels throughout the plant and contain significant detail about inventories, timing of operations, filling/emptying sequences, etc. The signals connecting the blocks contain the mass flow information of all nuclear material and bulk flows. The models need to be self-consistent, which is important for process monitoring since sometimes small changes propagate through a facility. The blue blocks represent measurement points and feed into an overall material balance calculation.

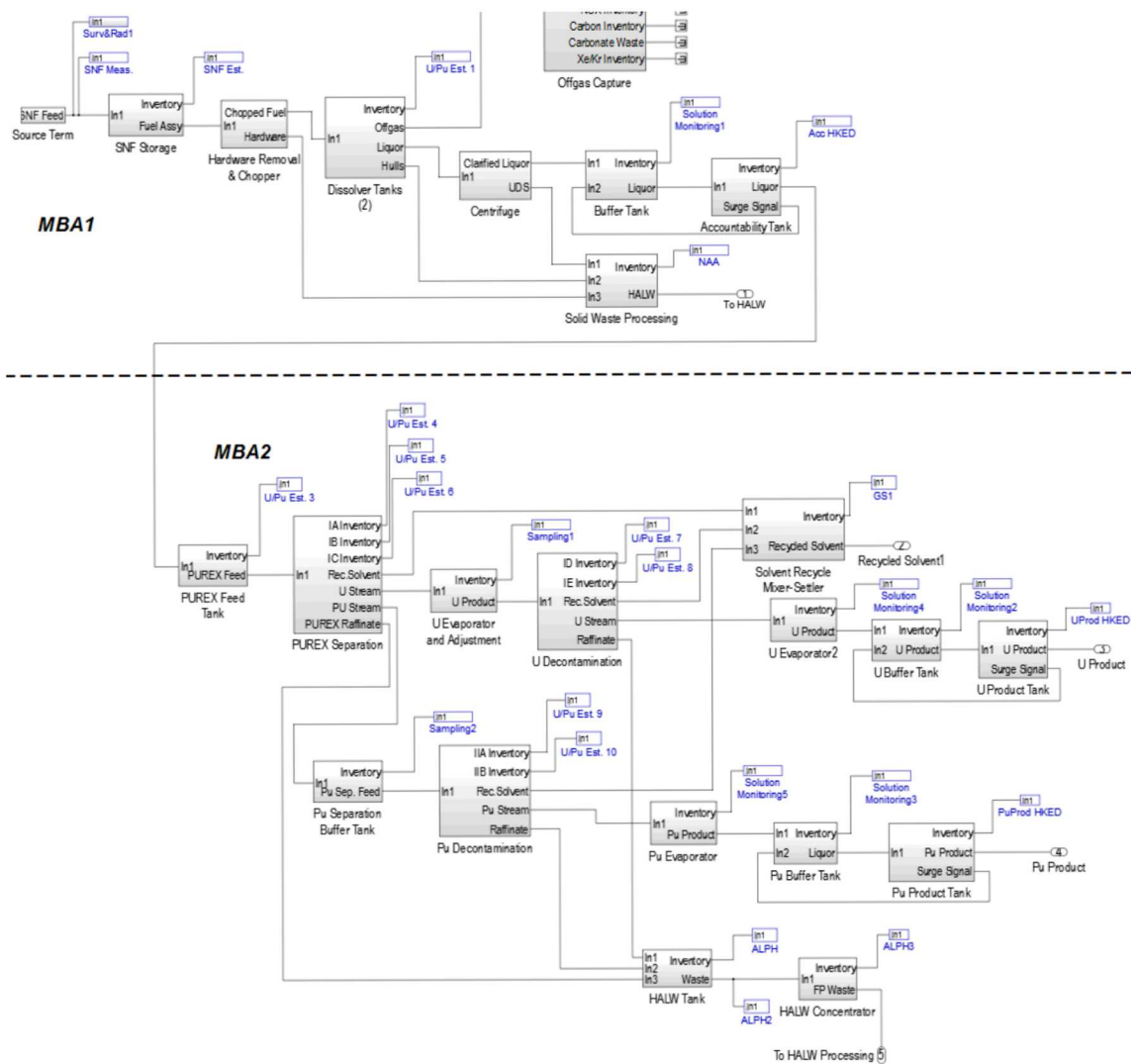


Figure 1. PUREX SSPM.

An SSPM Electrochemical version is shown in Figure 2. The operation of the model is very similar, but with differences appropriate to molten salt processing of nuclear material. All models contain the ability to turn on material diversions from various locations to examine the effect on overall plant safeguards. Capabilities include:

- Spent fuel source term library for user-defined runs
- Mass tracking of elements 1-99, full isotopic tracking, bulk solids/liquids tracking
- Integration with GADRAS (Gamma Detector Response and Analysis Software) [8] to simulate gamma spectra
- Customizable measurement points with user-defined error
- Automated calculation of Material Unaccounted For (MUF) and error in real time
- Statistical tests to set alarm conditions
- Diversion scenario analyses
- Integration with process monitoring data and physical protection systems

A bulk mass balance is relatively straight-forward to set up, and standard statistical tests can be used to detect material loss. This type of system already exists in the Solution Measurement and Monitoring System (SMMS) at Rokkasho [5]. This system is comprised of both joint use and operator-owned electromanometers to keep track of bulk material in the main separations area of the plant. Changes in one tank upstream can be correlated with changes seen downstream. The measurements are unattended, so ideal for IAEA use.

Bulk mass measurements should also be relatively straight-forward for pyroprocessing. Scales can be used for transfers of material and on certain pieces of equipment. A triple bubbler is being examined for salt level and density measurements for the larger salt vessels [6]. These measurements can be made with low uncertainty to detect direct loss.

Addressing Substitution Diversion

While the bulk balance can detect direct loss, additional measures must be in place to also detect a substitution loss. A substitution diversion involves removing material and replacing it with an equal amount of a surrogate in order to “beat” the bulk balance. The surrogate, though, is unlikely to match the gamma and neutron emission from the original material. Therefore, a safeguards approach may not necessarily need to determine if Pu has been diverted, but rather if there is an indication of material substitution.

NDA usually can only quantify Pu through indirect measurements, especially for samples with mixtures of transuranics and/or fission products. The estimation is part of the reason why measurement uncertainties are higher for NDA. However, substitution diversions provide indicators that can be measured with lower uncertainty than for Pu quantification. For example, if a dissolver solution is removed and replaced with uranyl nitrate, the fission product content will go down. This step change may be detectable through gamma measurements. Examination of specific fission product peak heights can indicate if a step change has occurred.

Past work on the Multi-Isotope Process (MIP) Monitor [7] provided a good first step in this direction. This work used gamma detectors to detect changes in reprocessing solutions to try to indicate off-normal events. Principle Component Analysis was used to examine changes. The work presented here is different in that multiple NDA signals are examined together with multiple bulk measurements to look for inconsistencies. A machine learning technique is being applied.

NDA Challenges

The use of gamma or neutron measurements have challenges associated with them for use in this approach. Gamma measurements provide the potential to measure a number of different peaks to indicate unusual activity. However, the Cs peak typically dominates spent fuel, so applicability will vary by location in a reprocessing facility. After fission products are removed, there is a higher chance of seeing additional peaks, but even small amounts of residual fission products can dominate spectra.

Self-shielding is another challenge. The shielding from canisters or the material itself blocks most of the internal gamma rays, making it difficult to rely on as an indication of material removal. Small, uniform samples may be required in order to eliminate self-shielding concerns.

Another problem is that real reprocessing facilities process a variety of spent fuel types. There is a natural variability in the isotopic content depending on the fuel feed. Therefore, changes in gamma or neutron emissions do not necessarily indicate a diversion.

Neutron measurements do not have a shielding issue, but are just a total gross count. With long enough counting times, neutron measurements can determine net decreases of actinides with lower uncertainty, but the measurement is mainly detecting Cm.

SSPM MODELING RESULTS

The new safeguards approach was examined using the SSPM for a generic pyroprocessing facility. Previous work had already examined the use of bulk balances for detecting direct material loss, so the focus of the analysis was on substitution diversions. Two substitution diversions were examined along with the effect on gamma spectra of the material from those locations. This work utilized the integration of the GADRAS code [8] with the SSPM for generating gamma spectra based on the isotopic inventories.

The first example is a substitution diversion of the electrorefiner salt. This scenario assumed that some amount of salt was removed and replaced with an equal mass of salt with depleted uranium chloride. The model ran assuming a varying spent fuel source term to simulate the mixture of fuels that run through a reprocessing facility. Figure 3 shows an example of a gamma peak during two different fuel batches for normal operation. The runs assumed taking a sample and gamma measurement right before the U/TRU extraction, immediately after the U/TRU extraction, and immediately after U/TRU drawdown. There is a small change in fission product content during these extractions, but the change to the peak is very small.

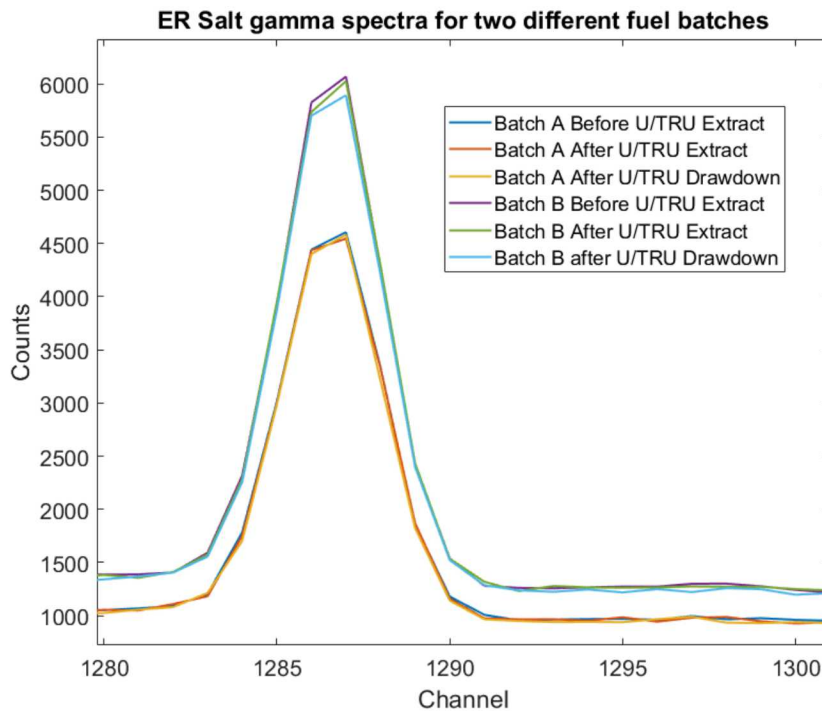


Figure 3. ER Salt gamma peak during two normal batches.

Then, the model was setup to run a substitution diversion scenario over one batch. Figure 4 shows the results of a simulated gamma spectra for a normal batch and the batch with the substitution. There is a normal variation in the relative height of each grouping of measurements due to the batch differences. However, the diversion case shows a spread in the peak height within the grouping for that batch. This spread is detectable and indicates a substitution diversion.

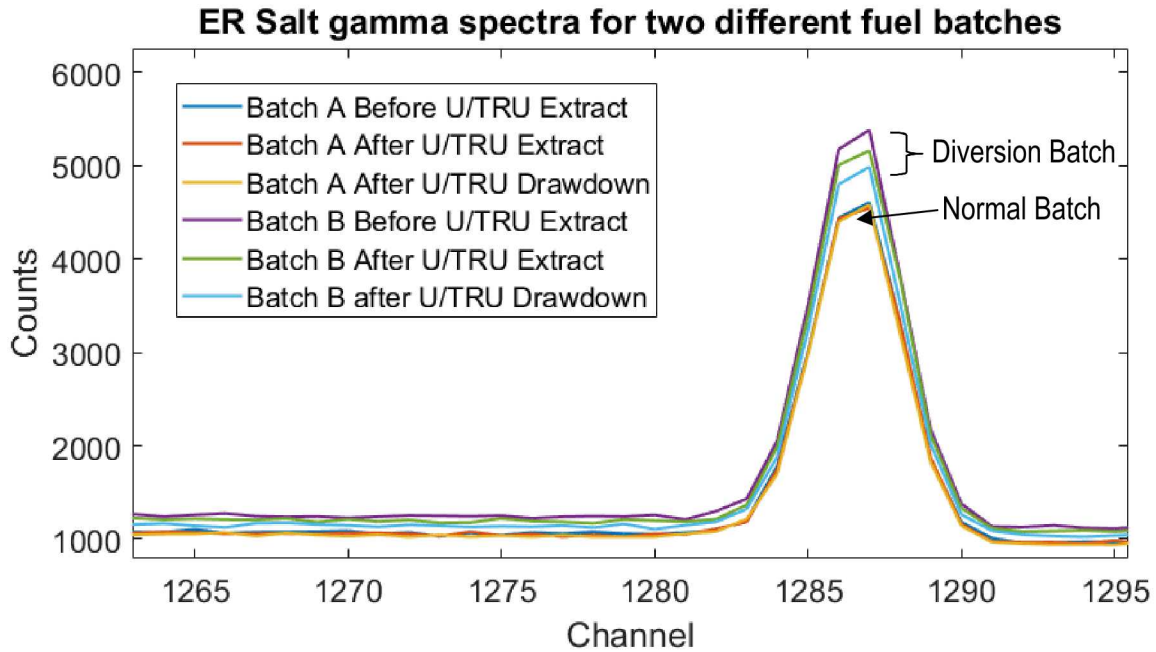


Figure 4. ER salt gamma peak during one normal batch and one substitution diversion.

The second example is a substitution diversion of the U/TRU product. This diversion assumed that some of the U/TRU product was removed and replaced with depleted uranium. Detection of the diversion using gamma spectra was a bit more complex. Figure 5 shows an example of four normal batches and one batch with a substitution diversion. The diversion case is indistinguishable from the other normal cases due to the variation in the fuel.

In order to find an indicator of diversion, the gamma peaks from the U/TRU product needed to be compared to the gamma peaks in the ER salt. Figure 6 shows a ratio of the peaks in the U/TRU product compared to those same peaks in the ER salt right before the extraction. The circles on the plot show the ratios under normal conditions, indicating a large amount of variability. The triangles show the ratios under a substitution diversion—the second peak shows a significant departure from the normal data, indicating a way to detect the diversion.

Both of the examples show that there are signatures of substitution diversions which can be detected even with normal variations in material flows. More work is required to analyze which gamma peaks provide the best indicators. Multiple peaks and additional measurements can be used. The next step is to develop a machine learning algorithm that can analyze all the data.

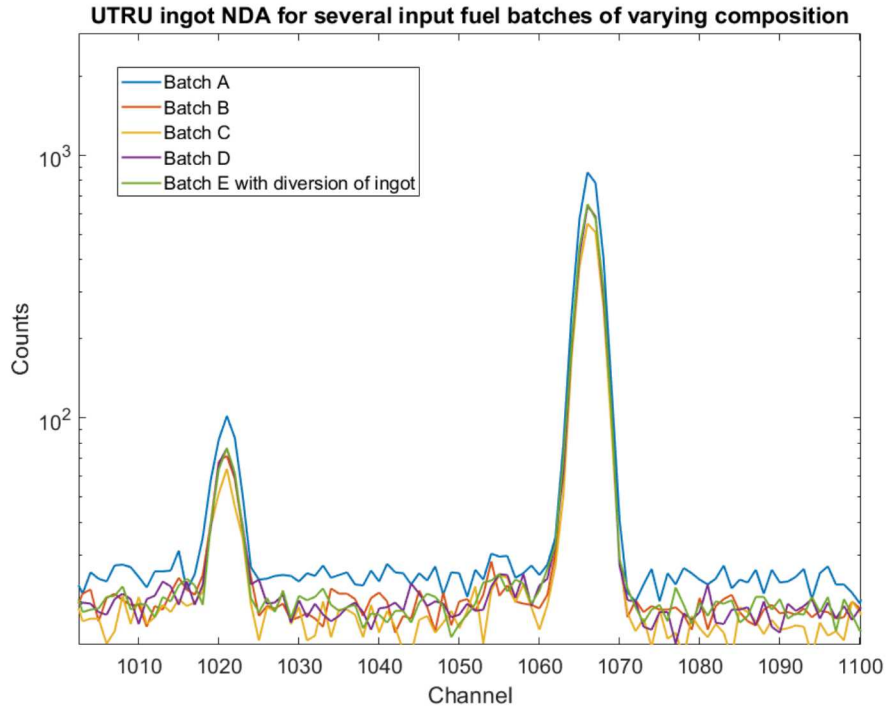


Figure 5. U/TRU product substitution compared to normal products

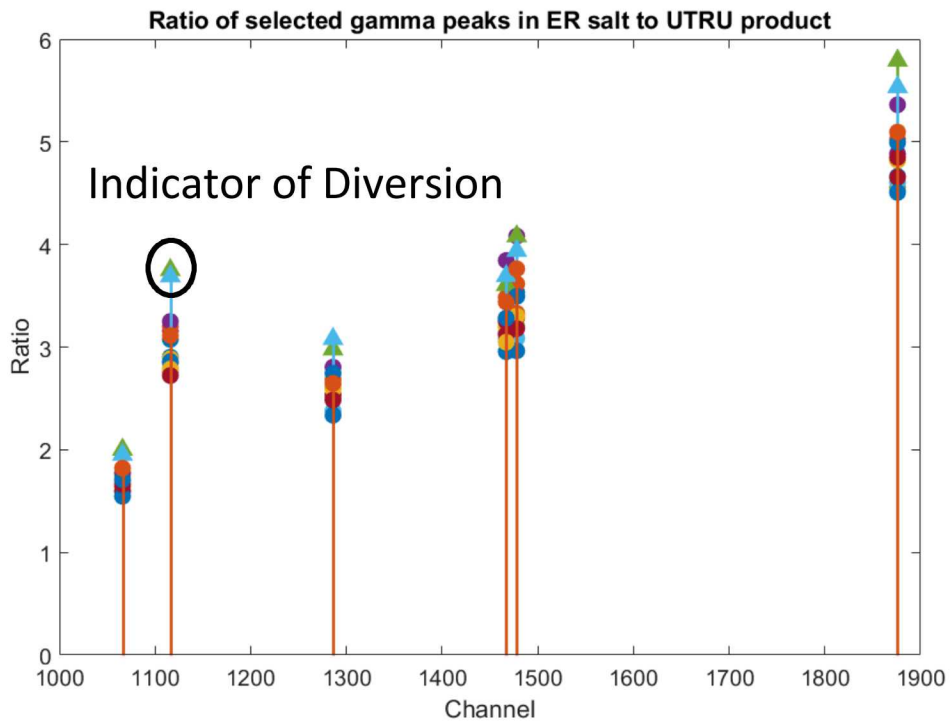


Figure 6. Ratio of gamma peaks comparing a diversion of the U/TRU product to normal runs.

OCSVM METHODOLOGY

The One Class Support Vector Machine (OCSVM) is an unsupervised machine learning technique that has promise for this application. It can be trained with normal data only, which is desirable since actual fuel cycle facilities will not be able to provide data for diversion scenarios. The OCSVM can take any number of input data streams and generate a boundary around normal data such that some defined percentage of points fits inside the boundary. Using normal data, the boundary can be set to achieve a desired false alarm probability. The OCSVM will produce a classification of 1 (normal) or -1 (off-normal) at each point in time that the calculation is applied. An alarm may be reached when a certain number of off-normal classifications occur in a row.

Future work will develop the machine learning approach in more detail. A significant amount of data analysis is required for this work since it requires multiple runs producing large sets of isotopic data that are then fed into GADRAS to generate simulated spectra. The analysis of the spectra then must be automated.

CONCLUSION

The new approach described in this paper is more feasible for a new facility, where the technology can be built into the plant. It would be difficult to apply these changes to an existing, operating facility. The approach requires a different way of thinking about the problem by breaking it down into the detection of direct and substitution diversion scenarios. The preliminary results shown here show promise in being able to detect indications of small substitution diversions using NDA measurements. A much deeper dive of the concept and training of a machine learning algorithm will be required to move this work forward.

ACKNOWLEDGEMENTS

This paper summarizes recent work funded through the U.S. Department of Energy Office of Nuclear Energy and National Nuclear Security Administration.

REFERENCES

1. "Guidance for States Implementation Comprehensive Safeguards Agreements and Additional Protocols," IAEA Services Series 21, International Atomic Energy Agency (May 2016).
2. S.J. Johnson and M. Ehinger, "Designing and Operating for Safeguards: Lessons Learned from the Rokkasho Reprocessing Plant (RRP)," PNNL-19626, Pacific Northwest National Laboratory (August 2010).
3. B.B. Cipiti et al., "Modeling and Design of Integrated Safeguards and Security for an Electrochemical Reprocessing Facility," SAND2012-9303, Sandia National Laboratories (October 2012).
4. B.B. Cipiti, "Process Monitoring Considerations for Reprocessing," *Proceedings of the Institute of Nuclear Materials Management*, Indian Wells, CA (July 12-16, 2015).
5. M. Ehinger et al., "Solution Monitoring Applications for the Rokkasho Reprocessing Plant," 7th International Conference on Facility Operations – Safeguards Interface (February 29-March 4, 2004).
6. B.E. Serrano, G.L. Fredrickson, and D. Vaden, "FY-12 Sensor for Measuring Density and Depth of Molten Electrolyte Technical Report" FCRD-MPACT- 2012-000309 (2012).

7. J.M. Schwantes et al., "FY09 Progress: Multi-Isotope Process (MIP) Monitor," PNNL-18940, Pacific Northwest National Laboratory (October 2009).
8. S.M. Horne et al., "GADRAS-DRF 18.6 User's Manual," SAND2016-4345, Sandia National Laboratories (May 2016).